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Development and application of prefabricated biogas digesters in developing countries

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ABSTRACT

Biogas technology has been promoted worldwide over the past decades, and its use has led to the recognition of the many benefits of domestic biogas digesters. Prefabricated biogas digesters (PBDs) continue to be developed, tested, and extensively applied in developing countries to compensate for the disadvantages of traditional domestic digester models. PBD prototypes are derived from three major types of domestic digester models, namely, the fixed dome, floating drum, and plug flow digesters. Two main streams of PBDs are represented by composite material digesters (CMDs) and bag digesters. PBDs also include off-site constructed ferro- or bamboo-and-cement digesters, as well as assembled digesters. The advantages of PBDs promote the development of different types of PBDs, and several nations have set up special instructions and institutions to promote PBDs. Challenges to PBD dissemination include inferior quality, high investment in CMDs, lagging PBD standardization, low levels of public information about PBDs, and lack of follow-up services. However, based on our literature research and field visits, it could be predicted that PBD technologies will be extensively applied worldwide in the near future.

Contents

1. Introduction

Biogas technology, also known as anaerobic digestion, has been used in organically loaded wastewater treatment for over 100 years [1]. This technology is recognized worldwide as one of the most energy-efficient and environmentally beneficial technologies for bioenergy production [2–10]. With proper handling, biogas for rural energy supply is sustainable, affordable, and has no negative effect on human health and the environment [11,12]. However, the complicated construction, high investment and maintenance costs, and difficult operation of mechanically equipped digesters have encouraged farmers to adopt simpler and cheaper anaerobic

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Table 1
Scenarios of DBD in the developing world.

No.	Region	Description
1	China	At the end of 2011, 41.68 million households (including centralized biogas supply) used biogas while the popularization rate was 34.7% in view of suitable households, thereby benefitting 160 million people in the rural areas [21].
2	India	As of 2011, 4.25 million domestic biogas digesters have been set up across India [22]. The National Advisory Board for Energy estimates that India has sufficient resources to sustain 16 million to 22 million domestic biogas digesters with 2 m^3 biogas production per day [23].
3	Nepal	Over 260,000 domestic biogas digesters have been installed in Nepal under the Biogas Support Program alone [24]. Based on the nationwide cattle population, approximately 1.3 million biogas plants can be installed in Nepal [25].
4	Bangladesh	Over 25,000 fixed dome biogas plants that mainly use cow dung have been installed in Bangladesh until 2008 [26]. Under the National Domestic Biogas and Manure Program, a total of 37,269 domestic biogas digesters would be financed during the 2006 to 2012 period [27].
5	Vietnam	Under the Biogas Program for the Animal Husbandry Sector in Vietnam, more than 14,000 DBDs have been installed from 2003 to 2012 [28], and 200,000 more DBDs are planned to be constructed from 2013 to 2018 [21]. The country's Biogas Program has won international recognition as a winner of the 2006 Energy Globe Award, the 2010 Ashden Award for sustainable energy, and the 2012 World Energy Award [28].
6	Cambodia	Under the National Biodigester Program, a total of 20,000 DBDs were installed between 2006 and 2012 [29]. In Cambodia, approximately 500,000 rural households could potentially install a DBD [30].
7	Africa	The level of biogas technology use for household purposes is extremely low in African countries [31]. Some of the first DBDs in the continent were set up in the 1950s in South Africa and Kenya [32]. Application scales of DBDs in African countries, unlike in Asia, have been ambiguous. An analysis [33] revealed that the exact number of plants installed in Africa is not known but that most units were installed in Tanzania (more than 4,000), Kenya, and Ethiopia. The number of units ranges from a few to hundreds in other countries. “Biogas for a Better Life: An African Initiative” set up the ambitious target to install two million DBDs (90% operation rate) by 2020 [34]. National programs in Africa are currently implemented in Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin, and Burkina Faso [35]. A market-based household biogas program implemented by a local non-governmental organization with limited support from international donors started in 2003. Since then, approximately 300 biogas systems have been built and adapted for the specific needs of households and institutions. This number of self-financed biogas plants indicates remarkable success for small and less developed countries (with 1.8 million inhabitants).
8	Latin America	Experiences with DBD began early in 1953 [36]. Promotion of biogas technology by national governments is relatively weak [37]. The experiences and lessons learned from Asia and Africa are being applied in Latin America [38], where biogas programs have been established in Peru, Bolivia, Colombia, and Guatemala since the 1980s. Nicaragua conducted a feasibility study in 2010 and initiated a new national biogas program in 2012 with a 50% dissemination target for PBDs. Bolivia also followed such a program and other countries are assessing their potential [1].

systems [13]. The development of rural household biogas systems is an important strategy to promote agricultural structural adjustment because it simultaneously reduces greenhouse gas emissions, increases rural incomes, improves sanitation, enhances ecology in rural areas, optimizes rural energy consumption structure, and improves the quality of both rural life and agricultural products [10,14–18]. Domestic biogas digesters (DBDs) have been effectively implemented worldwide, and governments and institutions have become involved in subsidy schemes, planning, design, construction, operation, and maintenance of biogas plants [19]. Several countries in Asia and Africa, particularly China, India, Nepal, Bangladesh, Cambodia, Vietnam, Kenya, Rwanda, and Tanzania, have launched massive campaigns to promote biogas technology [20]. An overview of current DBD development in developing countries is presented in Table 1.

Most DBDs in developing regions are constructed onsite and made of bricks and concrete. The poor construction of digesters, however, may cause leakages after a short period of operation. Once broken, digesters cannot be repaired easily for normal operation. Moreover, construction is often time consuming, lasting for as long as several months [39] because of a dependency on weather conditions. Appropriate plant models are required to adapt to various geological, topographical, and climate conditions, such as those in regions where the groundwater table is high, soils are rocky, and temperatures are relatively low during winter. Traditional DBDs currently being promoted are not particularly efficient, especially hilly regions [40]. Various types of alternative materials have been tested and used to replace conventional construction materials and overcome the weaknesses of brick and concrete household digesters. Fiber-reinforced plastic, modified plastic, and other new materials have gradually been used in the construction of biogas digesters and systems [41]. In contrast to an onsite-constructed digester (OCD), a prefabricated biogas digester (PBD) is produced offsite using materials with special physical properties. The present study introduces the scenarios of PBDs in developing countries and discusses the opportunities and challenges in these scenarios.

2. PBD prototypes

PBD prototypes are derived from traditional DBDs. Developing countries use three major types of DBDs, namely, the fixed dome digester, the floating drum digester (also called the telescoping digester), and the plug flow digester (also called the sausage-bag or channel digester) [42,43]. Some studies consider plug flow digesters and sausage-bag digesters as different types of digesters but these digesters are actually similar [25,44]. The advantages and disadvantages of these three types of DBDs are summarized in Table 2 [45,46]. PBDs can be processed and produced with different materials based on different DBD models. Most of the hard-structured PBDs used worldwide are based on the principle of hydraulics, i.e., the PBDs are composed of a digester body with a pressure compensation volume for the inside gas storage space in the outlet and inlet. An entire digester can sometimes be composed of a PBD in its top half and a concrete or plastered stone bottom half. Fig. 1 illustrates a complete PBD and top-half PBDs.

3. PBD types

Existing PBDs do not have an exact classification. PBDs are typically called “commercialized digesters.” These digesters are also called “three new digesters” because they typically adopt (i) new production materials, (ii) processes, and (iii) techniques. According to the China Association of Rural Energy Industry (CAREI), PBDs or commercial digesters are classified as fiber-reinforced plastic (FRP), plastic soft (PS), and plastic hard (PH)

Table 2
Advantages and disadvantages of three types of DBDs.

Digester type	Advantages	Disadvantages
Fixed dome digester	• Low initial cost • Long useful lifespan • No moving or rusting parts involved • Compact basic design • Less land required if built underground • Low maintenance	• Requires high technical skills for gas-tight construction • Difficult to repair in case of leakage • Requires heavy construction materials • Amount of gas produced in not immediately visible
Floating drum digester	• Simple and easy to understand operation • Visible stored gas volume • Constant gas pressure • Relatively easy construction	• High material costs because of extra steel drum • Short lifespan because of steel drum corrosion • High maintenance because of regular painting of drum
Plug flow digester/ Bag digester	• Low cost • Ease of transportation • Low construction sophistication • Uncomplicated maintenance • Less subject to climatic variations for fixed dome type [47]	• Relatively short lifespan • High susceptibility to damage • Low gas pressure • Limited creation of local employment • High impact on environment, less environmental-friendly [48]



Fig. 1. (Left) A complete PBD in China and (right) top-half PBDs in Bangladesh, photo courtesy: Shikun Cheng.

Table 3
Usual materials for PBDs.

Type	Materials
BD	For example: PVC (polyvinyl chloride, sometimes called geo-membrane), PE (polyethylene), HDPE (high-density polyethylene), PAMM (polymethyl methacrylate), LDPE (low-density polyethylene), and neoprene
CMD	For example: FRP, hard PVC, ABS (acrylonitrile butadiene styrene, also called engineering plastics), PP (polypropylene), HDPE, LLDPE (linear low-density polyethylene), DCPD (dicyclopentadiene)
Ferro- or bamboo-and-cement	Cement and wire mesh or bamboo

digesters [49]. Throughout developing countries, two main streams of PBD models are represented by composite material digesters (CMDs) and bag digesters (BDs). CMDs generally include FRP and PH digesters; whereas BDs indicate PS digesters, as defined in the classificationprovided by CAREI.

Off-site constructed ferro- or bamboo-and-cement digesters, which are considered as PBDs, are also applied in certain regions in the absence of advanced prefabricated materials and processes. The most frequently chosen materials for PBDs are listed in Table 3.

3.1. Bag digesters

BDs are the most popular PBDs that have been widely applied successfully because of their low cost and easy implementation and handling [50,51]. A BD is a sealed tubular structure made of soft plastic that may vary in size and thickness (Fig. 2). BDs are also referred to as balloon digesters, tube digesters, ball-type digesters, bladder digesters, and sausage-type digesters, in different regions of developing countries. The BD design was first developed in Taiwan in the 1960s [25] and subsequently introduced to other countries [52]. A BD consists of a long cylinder made of polyvinyl chloride (PVC), polyethylene (PE), or red mud plastic. BDs were developed to solve problems experienced with brick-and-metal digesters. BDs have been used in Colombia, Venezuela, Barbados, Costa Rica, and Cuba for 30 years. Other countries, such as Vietnam and the Philippines, have tested low-cost PE tube digesters since the 1980s [53–55] based on the BD model described by Pound et al. [56]. These digesters were later simplified by Preston et al. in Ethiopia, Colombia [57], and Vietnam [58]. The use of tubular PCV digesters that are more resistant should expand the lifespan of PE materials but at higher cost [59]. Gobar Gas Co. in Butwal first



Fig. 2. Installing a low-cost PE tube digester in Belize, photo courtesy: Maximiliano Ortega.

tested a PVC bag digester in Nepal from April 1986 to June 1986. Their study concluded that plastic BD can be successfully used only if the pressure inside the digester is sufficiently high and if PVC bags and welding facilities are readily available. Nepal Biogas Promotion Association estimated that areas within 1500–2500 m of sea level are potential areas for installing bag digesters in Nepal and that 40% of the households in these areas are potential buyers of a bag digester. Rough calculations suggest that around 170,000 bag digesters may be expected throughout Nepal [60]. In 1993, Vietnam began to develop flexible, sausage-shaped BDs or multi-layer, low-cost plastic sausages using locally available greenhouse plastic; this method is based on experiences gained in Cuba and supported by the United Nations Food and Agriculture Organization (FAO). According to the Strategy and Master Plan for Renewable Energy Development of Vietnam and the Ministry of Agriculture and Rural Development sources, about 2 million households have already installed biogas plants in Vietnam, including at least 1 million low-cost PE plastic BDs [61]. The low-cost PE tube or bag digester model is applied in Bolivia, as well as in Cuba, Peru, Ecuador, Colombia, Central America, and Mexico. In the low-cost PE tube or bag digester model, both ends of a tubular PE film with two coats of 300 μm are bent around a 6-inch PVC drainpipe. This film is then wound with a rubber strap of recycled tire tubes to yield a hermetic isolated system.

A study evaluated the performances of a rubber-balloon digester and a fixed-dome type Deenbandhu digester (both with 2 m^3 capacity) under hilly conditions [62]. and results showed that the daily average biogas production of the rubber-balloon digester was 33.7% less than that of the Deenbandhu digester. Changes in ambient temperature between day and night and between summer and winter affected the rubber-balloon digester more than the conventional plant [62]. Biogas production in BDs (0.1–0.32 m^3 biogas/m^3 digester/day) [63] is comparable with that in traditional digesters in India (0.21–0.83 m^3 biogas/m^3 digester/day) [64]. BDs are strongly recommended in rural areas where the membrane or balloon skin is not likely to be damaged and where the mean daily temperature is higher than 20 °C [65].

In Eastern and Southern African regions, BD technology was introduced in 1993 through a technical cooperation program conducted by the FAO in Tanzania; this program aimed to transfer and adapt technologies that had been previously validated in other tropical developing countries [66]. In 1994, a local NGO known as SURUDE (Foundation for Sustainable Rural Development) submitted project proposals to DANCHURCHARD and the FAD/SIDA Farming System Program (FSP) to promote low-cost BDs in Tanzania. SURUDE also popularized the technology in Kenya and Uganda [67] with support from the FSP.

The environmental impacts of OCDs and BDs were compared by means of Life Cycle Assessment and results showed that OCDs are more environment-friendly than BDs because the former employs appropriate construction materials. The high environmental impact of BDs may be explained by the type and short lifespan of the plastic materials commonly used in their construction. To improve the environmental performance of BDs, plastic use must be minimized, the lifespan of construction materials must be expanded, and more environment-friendly materials must be used. For instance, bioplastics may serve as a potential solution to reduce the environmental impact of this system [48]. It is best for BDs if it could to be sheltered from direct exposure to sunlight to expand their lifespan [68], especially in places with very strong sunlight (Fig. 3).

BDs are uniquely lightweight and they are easy to transport. The weight of a household-sized BD membrane is normally less than 30 kg. The components for installation can be handled by two people, and the BD can be transported using a small car or backpack. Fig. 4 presents the complete set of components of a typical BD system. BDs are particularly suitable for remote and/or mountainous areas where conventional construction materials are difficult to acquire and transport.

3.2. Composite material digester

The CMD originated from China [69]. and the country has developed numerous types of CMDs since the 1980s. A growing number of people have begun using CMDs in different regions. This new type of digester offers many advantages, such as easy mobility, long-term durability, and high productivity. A CMD is lightweight (i.e., this material is less than 1/10 of the weight of a typical OCD) and can therefore be transported and removed easily. A CMD also has good corrosion resistance to all types of organic acids. The high productivity of CMD stems from its absolute tightness and ability to withstand high pressure. Less time and effort is necessary to install the system. In fact, most of the required time is spent on earth excavation if the CMD is to be buried underground. Sufficient tightness results in high gas



Fig. 3. Plastic sheet shelter used to protect BDs in Uganda, Sub-Saharan Africa.



Fig. 4. Complete set of components of a PVC BD system in Nepal (left, photo courtesy: Heinz–Peter Mang) and in Kenya (right, photo courtesy: Flexi Biogas, Kenya, www.biogas.co.ke).

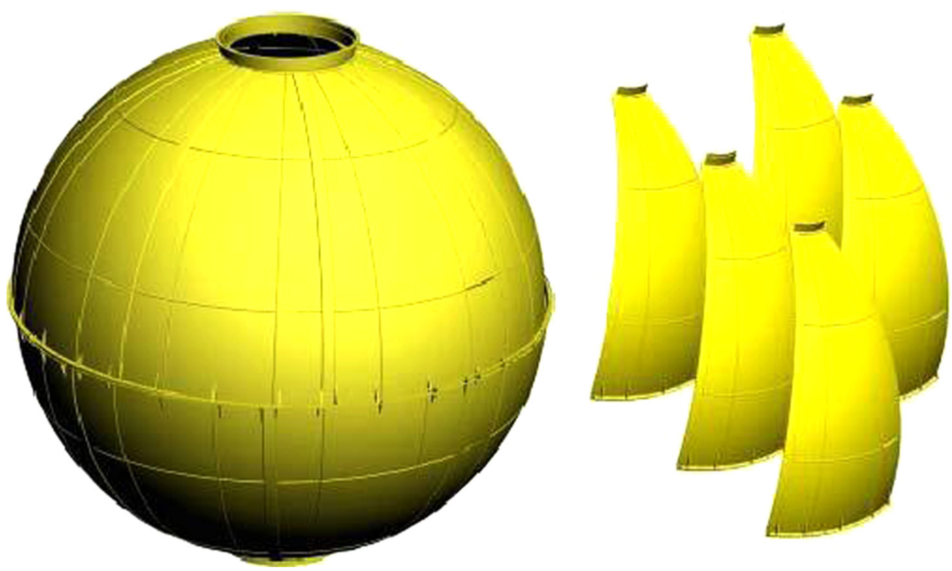


Fig. 5. Dismountable BD model. Each digester is composed of two parts (i.e., the upper hemisphere and the bottom hemisphere), each of which can be divided into eight pieces. This digester can be dismantled into 16 equal-sized pieces that may be stacked up for easy transportation, photo courtesy: Shikun Cheng.

pressure and may require the installation of other biogas equipment, such as a biogas lamp and a biogas generator, to exploit the entire biogas generation potential.

The FRP digester is a common representative of CMDs. The raw materials of FRP digesters comprise unsaturated polyester, gel-coated resin, chopped strand mat, and high-quality glass fiber cloth. The inner surface of the FRP digester is painted with a gel-coated resin to ensure tightness. The Chinese standard "NY/T 1699: 2009 Technical Specifications for Household Anaerobic Digesters of Fiberglass Reinforced Plastic" [70] establishes the four processes for manufacturing FRP digesters, including hand lay-up, sheet molding compound, resin transfer molding, and filament winding. Besides FRP digesters, other modified plastic digesters are also available. Fig. 5 shows dismountable digesters designed by a number of manufacturers; such digesters allow facile transport.

CMDs are a relatively new type of DBD used in countries such as Bangladesh, Cambodia, Nepal, and Vietnam [71]. Most of the CMD models have been introduced and modified locally, such as those used in large-scale pig farms. The CMD was introduced in Vietnam in 2008 [72]. the model for this system is produced in large numbers by several companies in Vietnam. The main advantage of the CMD is its high durability (its lifetime can extend beyond 20 years). CMD construction and installation are relatively time and labor efficient and they do not require a special trained mason to complete (Fig. 6). Moreover, the CMD can be excavated out and moved to other locations for secondary use; thus, this type of digester is suitable for areas undergoing urbanization. The digester may even be considered a collateral in bank loan schemes. Unfortunately, the CMD is fairly expensive. Over 10,000 CMD units have been installed in the northern and central regions of Vietnam [73]. As the number of large-scale pig farms in Vietnam continues to increase, the use of more CMDs may also be expected in the future [21].

In some coastal areas in southern India and southern Bangladesh, the process of manufacturing CMD originated from the shipbuilding industry because the composite materials used for the bottom or entire body of small ships and boats may also be applied to CMDs. In these countries, the production process technology is less efficient because a CMDs are mainly produced by hand (Fig. 7). In China, CMDs are produced using a 3000-ton heavy press machine and a 100-ton heavy mold. Prefabricated sheets are used as raw materials under 100 kg/cm^2 pressure and 140 °C temperature. A half digester is produced every 6–8 min. However, the factory process requires an initial investment of at

least 10 million CNY (1.6 million USD) [74], which is unaffordable for interested manufacturers in many developing countries where CMD application may be only at the nascent stage.

Another type of CMD based on commercially available water tanks (Fig. 8) is used in the developing world. In South Africa, the first prefabricated wastewater treatment system made of composite material has been tested [75]. CMD is particularly suitable for places where residential areas are rebuilt as a result of rural reconstruction and land reform measures or inheritance. Thus, the permanent locations of household biogas digesters are affected. Table 4 presents a comparison of PBDs and OCDs.

3.3. Other types and innovations in PBDs

In the early phase of the industrial development of PBDs, the ferro-cement type of construction was applied either as a self-supporting shell or as earth-pit lining. The vessel form was typically cylindrical, and plants under 6 m^3 were prefabricated. The ferro-cement gasholder in a fixed-dome plant requires special sealing measures; proven reliability is provided by cement-on-aluminum foil [49]. Ferro-cement biogas plants are recommended only in cases where special ferro-cement is available.

Bamboo cement can be used as an alternative for ferro-cement. Khadi Village Industries Commission (KVIC) in India initially attempted to use split bamboo in digester construction; however, this experiment failed because the bamboos were attacked by rats [76]. Fig. 9 shows ferro-skeleton-based and bamboo-skeleton-based digesters. The prefabricated Reinforced Cement Concrete (RCC) digester can also be categorized as a PBD; however, its advantages over the OCD are not apparent. Thus, the RCC is not considered and discussed in the present paper.

The advantages and disadvantages of typical PBDs are presented in Table 5 [40,74,77,78].

Another type of PBD is designed for kitchen waste disposal. Fig. 10 presents a new, compact, high-rate digester used for field tests. This new digester has several built-in engineering features to obtain maximum process efficiency in terms of solid reduction, high loading rate, and low hydraulic retention time and to prevent operational problems. This new, compact, high-rate digester can be prefabricated using different construction materials, such as sheet metal, FRP, HDPE, PP, or RCC.

Appropriate Rural Technology Institute (ARTI), which is an NGO based in Maharashtra, India, has developed a compact biogas plant that uses waste food rather than dung/manure as feedstock (Fig. 11). The ARTI compact biogas plant is a floating dome digester made from two cut-down HDPE water tanks, which are typically 0.75 m^3 and 1 m^3 in volume; the smaller tank functions as the gas hold at the top and the larger tank serves as the digester at the bottom. This model won the 2006 Ashden Award for Sustainable Energy in the Food Security category. The total cost of the whole system, including the digester, biogas stove, biogas pipe, and other ancillary facilities, is around Rs. 10,000 (200 USD). Such a system will be inexpensive if only food waste is used, regardless of labor maintenance. Even if the feedstock is purchased commercially, the daily running cost is only about 0.04 USD.

A novel portable digester was built from textiles supplied by FOV Fabrics AB, Sweden (Fig. 12). The shape of the digester resembles a pyramid with a working volume of 100 L. Using cow



Fig. 6. Installing a household BD at a project site in Vietnam, photo courtesy: Le Thi Thoa.



Fig. 8. Commercial water tank used as a CMD in Cambodia, photo courtesy: CARDO, Cambodia.



Fig. 7. (Left) Hand-made CMD and (right) machine-processed CMD, photo courtesy: Shikun Cheng.

Table 4
Comparison between PBDs and OCDs.

Parameter	OCD	BD	CMD
Cost	Typically, 300 USD to 800 USD	20 USD to 200 USD; significantly less than that the cost of OCD	300 USD to 100 USD; similar to or slightly higher than OCD
Construction cycle	Up to 20 days	Less than 1 day	Typically 1 to 2 days
Service life	More than 10 years with adequate maintenance	Varies significantly depending on materials; generally less than 10 years	More than 25 years; even longer for underground types
Maintenance	Frequent, generally once every two years	Almost none	Almost none
Transportation	Extremely heavy construction materials; transportation cost accounts for relevant fraction of total investment	Between 10 kg and 100 kg; extremely easy to transport (package occupies small space)	Between 50 kg and 200 kg; easy to transport (can be dismantled)
Mechanical property	Good	Easily damaged	Good
Insulation	Normal; easily influenced by ambient temperature	Normal, easily influenced by ambient temperature	Good with low coefficient of heat conductivity
Tightness	Bad; requires skilled workmanship for sealing	Depends on material properties; easy to repair in case of leakage	Good; resistant to acid corrosion
Water absorption rate	High; corrodes easily under high underground water level	Low; suitable for regions with loosen soil and high underground water level	Low; suitable for regions with high underground water level



Fig. 9. (Left) Ferro-skeleton-based digester and (right) bamboo skeleton-based digester, photo courtesy: Heinz-Peter Mang.

Table 5
Advantages and disadvantages of PBDs.

Category	Advantages	Disadvantages
BD	• Low cost; easy for farmers to accept • Easy to transport and install • The slurry can be agitated easily by the movement of the digester body and the continuous flow inside the digester • Suitable for places with high groundwater table	• The membrane is sensitive to sunlight, falling objects, people, and animals; thus, it has a short life and can be easily damaged • Sediment that can be accumulated in large amounts inside the digester is difficult to remove • It cannot maintain temperature; thus, it operates poorly during winter
CMD	• Gas-tight, watertight, and has high gas pressure • Saves construction area because it is buried underground • Saves installation time; does not require trained masons • Can be moved to another location when necessary • Simple operation and maintenance • Installation of additional biogas equipment and accessories is possible	• High initial investment • The complete CMDs tend to sink if the groundwork is not strong enough [79,80] • Available only in a few digester volumes; thus, owners and users have limited choice
Ferro-cement digester	• Low construction costs particularly compared with the potentially high costs of masonry plants • Low material input	• Substantial consumption of good-quality cement and expensive wire mesh • Construction technique has not been adequately time-tested • Requires special sealing measures for the gas-holder

manure as an inoculum, biogas production increased steadily with increasing loading rate; in fact, the average biogas production (organic loading rate, 1.0 g VS/L/day) was 569 L biogas/kg VS/day, which is equivalent to 90% of the theoretical yield [3]. Today, innovators are closely collaborating with local companies in Indonesia, Vietnam, Brazil, and India to build textile digesters.

Portable and onsite-assembled digesters have been invented as the PBD market has expanded. This type of digester is a dismountable unit mainly used to treat green and kitchen wastes. It provides a plug-and-play method of applying anaerobic digestion technology. Fig. 13 presents a typical portable and onsite-assembled digester.

4. Opportunities to develop PBDs

DBD dissemination has increased throughout developing countries. However, the performance of traditional OCDs generally remains at suboptimal levels. In 2006, well-operating household digesters reportedly accounted for less than 60% of the total number of digesters in China [81]. A survey of 66 household plants in Bangladesh in 2008 found that 3% of household digesters were functioning without defect, 76% were defective but functioning, and 21% were defective and not functioning [82]. A nationwide survey of 94 household plants in Nepal showed that the well-operation ratio is about 53% in practice [83]. Besides plumbing issues, most faulty plants are nonfunctional because of damages at the slurry chamber, feedstock unavailability, or cracks in the foundation [84]. These findings provide opportunities to develop PBDs in a factory with quality-controlled measures. CMDs possess high mechanical strength [85] with good gas tightness and long service life. Moreover, well-packed and covered CMDs are adequately insulated to maintain stable internal temperatures [86]. Gas leaks through the dome are always the main problem in fixed dome OCDs, especially in areas where skilled labor and good quality materials are scarce. This problem is common in many regions of developing countries. PE or PVC domes, which prevent gas leakage and ensure easy installation, are available for this type of digester. The construction time can be reduced from 3 weeks for an OCD to only 6 days with a PE dome. It is also suitable for repairing and updating existing conventional digesters.



Fig. 10. Compact, high-rate digester for kitchen waste disposal, photo courtesy: Dr. Johny Joseph.

PBDs are suitable for the following cases:

1. sites where the groundwater level is high, such as in coastal areas where constructing onsite brick, stone, concrete, or molded digesters is difficult;
2. sites where the quality of digester construction cannot be controlled while guaranteeing gas and water tightness;
3. sites located in remote and/or mountainous areas where conventional construction materials are difficult to acquire and transport;
4. sites with inadequate supply of conventional construction materials and limited availability of specialized labor force, which results in increased construction cost; and
5. sites where residential areas are modified and rebuilt, which affects the permanent locations of conventional digesters.

A number of countries, particularly China and India, have set up specific instructions or institutions to promote the new industry of PBDs. The scenarios are presented in Table 6. For instance, according to the 11th Five-Year Plan of the Indian National Biogas

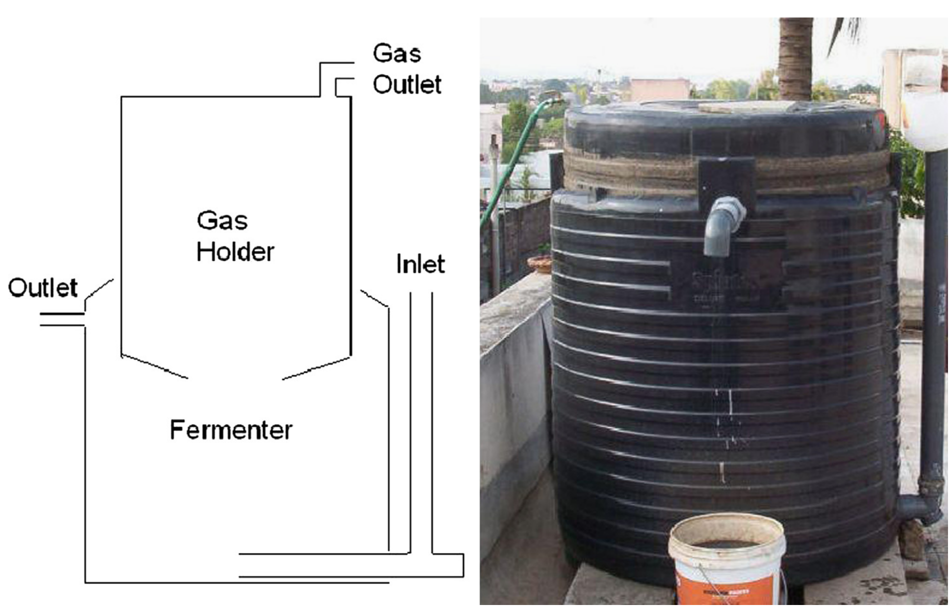


Fig. 11. ARTI compact biogas digester, photo courtesy: Appropriate Rural Technology Institute.

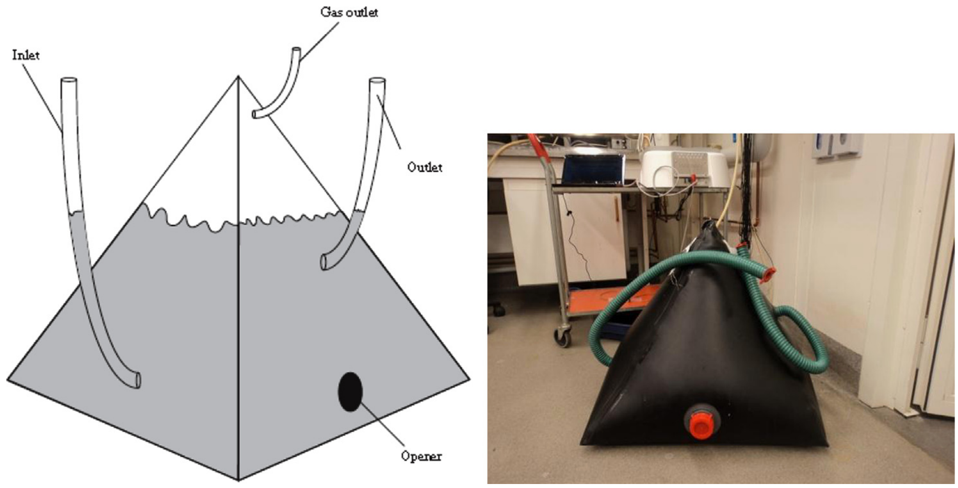


Fig. 12. Portable textile digester for testing, photo courtesy: Karthik Rajendran.



Fig. 13. Typical portable and assembled digester in Malaysia (1—Gas pipe; 2—Upper part; 3—Seal; 4—Bottom part; 5—¢110 Seal ring; 6—Flange; 7—Connecting pipe; 8–90° elbow; 9—Butterfly gate; 10—blind plate; 11—¢200 Seal ring; 12—Inlet; 13 - Cover; 14—Outlet; 15—Slag outlet), photo courtesy: Shikun Cheng.

and Manure Management Program (NBMMP), prefabricated models of biogas plants are available based on HDPE, FRP, and RCC materials [87].

In developing countries, DBDs in rural areas mainly target animal dung/manure. Another mainstream type of BD is employed to treat domestic sewage. In developing areas, traditional wastewater treatment systems that adopt anaerobic digesters are usually built with bricks and reinforced concrete materials. These materials are inexpensive and widely available. Prefabricated modules have been introduced in recent years. Prefabricated systems present obvious advantages over the traditional ones: (1) the biogas plant quality of prefabricated systems is better than that of traditional ones because of industrial-level quality control; (2) prefabricated systems exhibit sufficient mechanical strengths with good air/gas tightness and a long service life; (3) under normal conditions, good insulation maintains relatively stable temperatures inside the reactor; (4) light weight facilitates easy transport; and (5) as the installation time is short when the systems and/or modules are manufactured off-site. In such case, CMDs can be well integrated into wastewater treatment facilities. Some countries such as China, South Africa, and Indonesia have applied CMDs in prefabricated wastewater treatment systems (Fig. 14). This will be another opportunity for applying PBDs in developing countries [97].

5. Challenges in PBD development

Today, the development of the PBD industry in developing countries remains unconsolidated and faces barriers and challenges.

First, the PBD production continues to rely on manual manufacturing processes in many places. Thus, PBD quality cannot be effectively controlled. Some enterprises adopt inferior materials or the jerry-building method for manufacturing to reduce production costs. In general, potential clients (or future users) cannot distinguish good from bad quality; thus, poor-quality products may disappoint users [98]. For instance, FRP digesters made of inorganic materials (i.e., MgO and $MgCl_2$) with high water-absorption capacity were introduced to the market in the early days of the industry; these digesters hindered PBD dissemination. Therefore, market entry certification and production license systems must be established to ensure product quality. Local governments and industry associations must be responsible for evaluating high-quality products and releasing a list of recommended products for reference [99]. Demonstration projects must also be conducted at the initial phase of dissemination to inform the public about the benefits of PBDs. Public comprehension must be increased to improve the acceptance of PBDs in the market.

Second, investment in CMDs remains unaffordable for users in rural areas because of raw material scarcity. In many developing countries, the chemical industry is underdeveloped; raw materials for composite models, such as fiberglass, carbon fiber, and polyester, are 100% imported [77]. For instance, a BiogasPro digester produced by AGAMA Energy in South Africa is sold at a retail cost of 2800 USD. By comparison, a normal BD only costs 20–200 USD [72]. Therefore, low-cost BDs are more popular than CMDs in most developing regions. In fact, CMD importation greatly increases the cost of the system. In Uganda, the expected cost of each BD is about 100 USD, whereas the actual cost is about 550 USD (including importation costs) [100]. Therefore, low-cost BDs are more popular than CMDs in most developing regions. In fact, importation of CMDs greatly increases the cost. In Uganda, the expected cost of each BD is about 100 USD while the actual cost is about 550 USD including importation cost[68]. This expense is very costly for many rural householders. In Nepal, BDs cost around 35,000 NRs (about 350 USD) per plant (i.e., 30–69% cheaper than the conventional GGC2047), but the local price must be much lower because the quoted price includes importation fees. Local manufacturing of PBDs is strongly recommended to reduce importation costs and promote PBD use.

Third, few subsidies for PBDs are available. In developed countries, subsidies to promote DBDs may be obtained. However,

Table 6
Opportunities to promote PDBs in different countries.

Countries	Opportunities to promote PBDs
China	1. Special PBD groups have been established under CAREI. 2. Over 100 enterprises are working on PBD production, and the market has an annual capacity of 500,000–1,000,000 sets. 3. The standard "NY/T 1699: 2009 Technical Specifications for Household Anaerobic Digesters of FRP" was released by the Ministry of Agriculture (MoA) in 2009. 4. Between 2011 and 2012, CAREI collaborated with China Biogas Society, China Composites Industry Association, and China Plastics Processing Industry Association to conduct a survey to evaluate PBD manufacturers and introduce 20 manufacturers for demonstration and popularization. Afterward, the MoA chose three of these manufacturers to present demonstration projects [88].
India	1. Many companies and institutes, such as BIOTECH and ARTI, have engaged in PBD innovation. 2. PBDs have appeared on the list of Approved Models of Family-Type Biogas Fertilizer Plants under the NBMMP; these models includes the prefabricated RCC fixed dome model, prefabricated RCC digester KVIC model, prefabricated HDPE-based complete/dome Deenbhandhu model, prefabricated BIOTECH-made FRP, prefabricated HDPE-based KVIC-type floating dome model, Shakti Surbhi FRP-based floating dome KVIC type, Sintex-made plastic-based floating dome KVIC type, bag type (flexi model), etc.
Vietnam	1. Local enterprises have been engaged in innovation and manufacture of PBDs and the market has taken shape to some extent. 2. Composite plants have been introduced within the project "CARE International in Vietnam's Options and Ownership: Water and Sanitation for Rural Poor in the Mekong Delta" in Ca Mau and Soc Trang provinces [89]. 3. A proposed project "Optimization of Household Composite Biogas Project" will concentrate on optimizing current CMD designs and preparing standardized installation guidelines in Vietnam. Composite BDs have been tested and evaluated [73,90].
Asian countries, such as Bangladesh, Nepal, the Philippines, etc. African countries, such as Kenya, Ethiopia, Tanzania, etc. American countries, such as Belize, Colombia, Cuba, etc.	1. Numerous low-cost plastic tube digesters have been tested and installed since the 1980s, and the most common materials include PE, PVC, and HDPE [91]. Several countries have released manuals highlighting low-cost plastic tube digesters [92,93]. 2. Low-cost plastic tube digesters have been proven to have a high degree of acceptance among small-scale farmers with financial constraints [55,94,95]. 3. The technology of composite digesters is relatively mature in China; thus, samples have been imported from China to be duplicated for local production. 4. When promoting biogas technology by international organizations, such as the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Netherlands Development Organization (SNV) [96], PBDs have been considered as OCD substitutes. Technical support from developed countries, such as FOV Fabrics AB from Sweden and SimGas and Ecofys from the Netherlands, is available.



Fig. 14. CMD application in prefabricated wastewater treatment system in Indonesia, photo courtesy: Ms. Prawisti Ekasanti.

no subsidies are found for PBD innovations, e.g., the Indian ARTI compact digester. Therefore, owners pay the full cost of the entire system, although some suppliers accept payment in installments. This drawback definitely limits the development of the PBD industry. Some organizations have injected money and resources for innovation and inspiration into the construction of PBDs. Once these inventions are applied in the market, promoting these systems without subsidy will be very difficult, particularly when no economic advantage over DBDs is noted. To overcome the high cost of CMDs, governments must establish preferential policies, such as providing the same subsidies to CMDs and OCDs. These preferential policies must feature incentives that will motivate manufacturers to develop high-quality and affordable products for CMD users. Research on low-cost PBDs must be emphasized, and enterprises must develop new products that are economically affordable, technically reliable, highly adaptable, and easily transportable. Governments should financially support necessary research and development efforts

Fourth, the standards for PBDs are insufficient. Non-optimization of designs and lack of operation guidelines are the main concerns. Inappropriate designs, the absence of standardized gas-piping and gas meters, and the lack of operation guideline lead to significantly reduced PBD working efficiency [101]. China has set up the most complete DBD standardization system; however,

only one standard that focuses on PBDs has been released [102]. Moreover, this regulation is difficult to implement. In other countries, both DBD and PBD standards are lacking. Fortunately, some countries, including Bangladesh and Cambodia, have begun to set up PBD standards. BD standards must be formulated immediately, and related standards for testing methods, in addition to a detailed construction manual, must be established. Most of the newly improved PBDs are still in the pilot and exploration stages; the formulation and promotion of standards is crucial in advancing the sound development of PBDs. Concerned authorities at different levels must guide PBD normalization and train relevant technical staff.

Fifth, the public has limited awareness of PBDs, particularly CMDs. Only 70% of the surveyed households in Vietnam have heard about CMDs [103]. PBDs are relatively new in many African regions where DBDs and BDs have been introduced. A sample size of 60 households that adopt BD technology was studied in Kenya in 2009. Although many consumers (77%) were satisfied with the BD, many of them were disappointed because the digester did not meet their lighting needs. Furthermore, fluctuations in gas production, especially in the morning and late evenings, are very inconvenient and result in longer cooking hours. The issue of low gas production in the morning and evening is based on how well the digester is insulated from weather elements, such as sun, rain, and wind, which can be resolved by training.

The development of BD technology faces a number of challenges, including lack of technical information sharing among farmers, donor dependency syndrome, perceived high cost of BDs installation. Challenges that may impede the accelerated adoption of BD technology include lack of manpower to train and install the BDs when and where necessary [94,95].

Follow-up service has an important function in disseminating DBD use. A large number of DBDs are abandoned once cracked. Thus, manufacturers who are responsible for PBD sales and construction must establish a complete follow-up service system that will be supervised by the government. Special funds for follow-up services should be allocated to biogas enterprises.

6. Application potential of PBDs

In Asia, the development and use of PBDs is a promising model. Compared with traditional OCDs, PBDs have a smaller market share but significant market potential. FRP digesters and PVC BDs are the most popular PBDs to be exported from China to other countries. For instance, Bangladesh has imported FRP digesters from Yunnan and adopted half-FRP digesters while duplicating the other half with local technology. In Nepal, soft PVC BDs have contributed to the implementation of the Nepal Biogas Support Program; this type of PBD has been proven suitable for special plateau terrains where transportation is difficult. In India, several new inventions related to PBDs exhibit local creativity, and PBD models approved under the NBMMP have been promoted by local manufacturers. In Vietnam, low-cost PE tube biodigester have been proven to be a cheap and simple method of producing biogas for small-scale farms [104]. Although CMDs were introduced only in 2008, over 10,000 CMDs are currently used in the northern and central regions of Vietnam [77]. In Cambodia, different PBDs, including retrofitted water tanks, are being tested by the Cambodian Agriculture Research and Development Organization. PBDs are also being disseminated and applied in Malaysia, Indonesia, Myanmar, and the Philippines.

In Africa, PBDs are applied in South Africa, Kenya, Uganda, Rwanda, Sudan, Congo, Comoros, Mozambique, Madagascar, Sierra Leone, and Tanzania, and most of these PBDs were imported from China under the Aid to Africa Plan. To a certain extent, South Africa initiated and currently leads the African continent in terms of PBD use. The PBD called AGAMA BiogasPro (Fig. 15) was developed in South Africa, and its customers include farmers, rural schools, eco-lodges, and “green” households, which are mainly rural; some urban customers also use this PBD. AGAMA BiogasPro distributors can also be found in Tanzania, Botswana, Namibia, and Mozambique [105]. The AGAMA BiogasPro has earned the inventor's second prize at the South Africa Cleantech Competition [106]. Some other countries have also implemented a large-scale PBD program. For example, Lesotho, which is a small country in South Africa, plans to import 100 PBDs and install these in Berea under the instruction of Chinese technicians.

Some countries in Latin America have set up national biogas programs supported by the Latin American Energy Organization. However, PBDs are not yet considered mainstream equipment. CMDs are only being tested by research institutes engaged in biogas technology. Commercial CMDs are not yet available because experience in using CMDs is lacking and the long transportation distance from Asia to Latin America causes inconvenient importation. Low-cost BDs are more popular than CMDs and have been widely applied in Bolivia, Peru, Ecuador, Colombia, Honduras, Mexico, Guyana, Belize, and several other countries. Demonstrations of PBDs, particularly CMDs, are necessary to reveal the advantages of these mechanisms. Over the past few years, countries such as Chile, and Haiti have suffered from earthquakes that destroyed most of their infrastructure, including BDs. The restoration of OCDs to their original state to meet the energy demands of rural reconstruction areas is nearly impossible under short periods

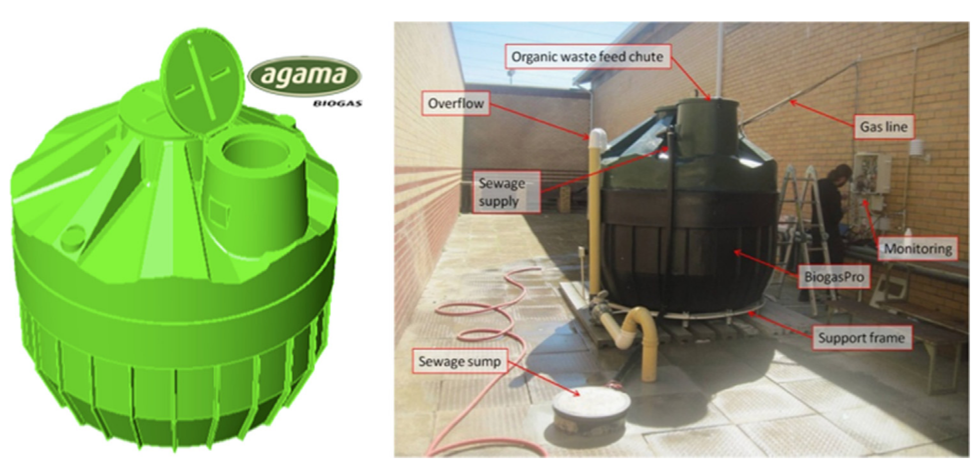


Fig. 15. Design sketch and real product picture of “AGAMA BiogasPro” developed in South Africa, photo courtesy: AGAMA BiogasPro, South Africa.

of time. PBD utilization is ideal in places where residential areas are being rebuilt, which affects the permanent locations of OCDs. Many places in Latin America are located in the global seismically active belt; thus, during earthquakes, PBDs may have a key function in restoring local energy supply systems, particularly in rural areas. Due to their lack of insulation, biogas production rates are about 30% lower in BDs than in fixed dome digesters. In this case, BDs may be adapted to Andean conditions by providing digester insulation and substituting a simple roof used by greenhouses in tropical regions [48].

Aside from Chinese and local enterprises, companies from developed countries are also developing the products for African and Latin America markets. Three representatives of these companies are FOV Fabrics AB from Sweden and SimGas and Ecofys from the Netherlands. FOV BIOGAS provides high quality BDs that can ensure uninterrupted production and lifetime of over 10 years; however, the price of such BDs is much higher, costing roughly 50 USD/m^3 to 120 USD/m^3 digester volume. SimGas biogas systems are prefabricated using a numerical control machine with HDPE. SimGas has local partners in Tanzania. Ecofys has developed the prefabricated Ecofys plastic bag digester, which is specifically designed for farming households. Five prototypes have been tested successfully in South Africa, Tanzania, Guatemala, Brazil, and the Netherlands. All of these companies are currently looking for partners to deploy their products on a larger scale.

7. Conclusion and outlook

Low-cost household digesters are considered an appropriate technology in expanding modern energy services in developing countries. These digesters have spread successfully in developing countries over the last several decades. A number of countries have established massive national campaigns to popularize biogas technology.

PBDs, such as low-cost BDs and CMDs, have been developed and applied in developing countries to overcome the disadvantages of OCDs, which include long construction periods, relatively short lifetime, and heavy construction materials that result in high transportation costs.

PBD advantages, such as low cost, high mobility, high durability, high insulation, and high resistance to corrosion, can stabilize and optimize the operational status of DBDs. Several countries have established specific instructions and organizations to promote PBDs and provide opportunities for the development of such equipment. The advantages of PBDs are apparent; however, the disadvantages that create barriers to PBD development in developing countries cannot be ignored. These challenges include inferior PBDs that disappoint users, high investments in CMDs that lead to affordability concerns, underdeveloped PBD standardization systems, limited public awareness about PBDs, and follow-up service issues.

China exports large numbers of PBDs to other countries, which makes these products accessible to local users. Therefore, more product marketing activities from local suppliers and distributors are necessary to increase the number of people who are aware of the product, thereby increasing potential customers. The PBD industry requires substantial effort to become more prominent in developing countries. The use of PBDs is an irresistible major industrial trend that is expected to provide a cheaper, safer, more durable, and more efficient technique of producing energy in developing countries. Increased demands for PBDs in the future is expected.

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